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14. ABSTRACT
The HPM sources basic research program of the Air Force has a major emphasis on the pulse shortening problem. This includes collaborative work in universities and the Phillips Laboratory. We have demonstrated two fundamentally different HPM sources which radiate rf power in excess of 1 GW and are not limited by pulse shortening (up to our 300 nsec pulse length): the MILO and Injection Locked RKO. While the fundamental physics of these sources are different, they both have generated in excess of 100 J. We will discuss the physics of how the pulse shortening was eliminated, up to the limits of our pulse power driver. We report on experiments and computer simulations investigating techniques to overcome these pulse shortening issues. We also report on our plans for the coming year to try and extend the electron beam (to 600 nsec) and rf pulse length (up to 500 nsec).

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HPM, pulse shortening, GW, gigawatt, high power microwave

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Results of Research on overcoming Pulse Shortening of GW class HPM sources

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1. INTRODUCTION

A common problem encountered by High Power Microwave (HPM) sources is that of rf pulse shortening. This problem is observed when the radiated rf pulse has a shorter time duration than applied high voltage pulse. Few if any solutions have been found to overcome this phenomenon of pulse shortening. We report here on two different HPM sources, the injection locked-RKO and the Hard Tube MILO, which have been made to produce rf power to the termination of the electron beam pulse. Both sources take about 100 to 150 nsec to begin the rf pulse, but that is a common characteristic of self-oscillators.

2. THE INJECTION LOCKED-RKO

Our version of the RKO has been previously published, so the full details will not be repeated here[1,2]. Briefly, an annular electron beam is emitted through a converging magnetic field into a pipe only slightly below cutoff for the chosen rf frequency. Two coaxial $\frac{3}{4}\lambda$ cavities separated by less than $\frac{1}{2}\lambda$ form a coupled cavity system with two modes. The first mode has the electric field parallel in the two rf gaps and the second mode has the electric field anti-parallel in the two rf gaps. The coupled cavity system is unstable only for the first mode with the rf electric field parallel in both modulating gaps. The first cavity is driven by an external magnetron to provide the proper initial condition for the $\frac{3}{4}\lambda$ mode to be excited without competition from the $\frac{1}{4}\lambda$ mode. This coupled cavity system produces a modulated rf current on the electron beam of order 60% of input beam current. However, due to the high space charge reduction of the kinetic energy, not much kinetic energy remains to extract rf power. We inserted a center conductor [3] following the coupled cavity system to change the boundary condition on the modulated beam. The center conductor also employed a coaxial cavity opposite the extractor gap to allow the axial electric field to drive the output transmission line. The RKO is shown in Fig. 1.

We have shown data [4] which indicates that with a constant applied voltage the electron beam current grows in time. Initially, this was believed to be typical diode collapse. However, during a brief experiment where the applied electric field was increased, by decreasing the anode-cathode gap, the current became more constant. This shows that the increase in the current must be associated with a growth in the emission area of the cathode. The ramping current was found to be the source of the pulse shortening, at least to the 300 nsec pulse length available from our pulser.

Friedman's circuit model of the RKO [5] allows one to determine the change of the rf frequency with variation of the electron beam current. One finds that a variation in excess of two to three kA in the electron beam current will cause enough of a frequency change due to beam loading of the cavities to no longer be resonant with the unstable mode of the coupled cavity system. We verified this conclusion by a series of experiments where the external magnetron frequency was varied. The maximum electron beam modulation occurred at increasing beam current as the magnetron drive frequency was increased from the unstable coupled cavity frequency.

The result of the output rf frequency varying with the electron beam current caused us to fabricate several new cathode tips. Two of these tips were a bulk carbon tip, and a steel tip with carbon fibers coated with Cesium-Iodide salt arranged in a cylinder around the steel tip. These two cathodes provided a much more constant current for applied fields of order 100 kV/cm. The carbon cathode yielded a 10 kA pulse with ≤5 kA of variation during the beam pulse. The carbon fiber cathode delivered 8.5 kA with less than 1 kA of variation during the beam pulse. The carbon cathode drove the RKO to produce an rf pulse of amplitude 1.5 GW and integrated energy of 170 J, and the rf pulse terminated as the beam pulse ended. The measured ratio of rf power to beam power was 30% and the energy efficiency was 15%. The carbon fiber cathode driven RKO yielded a lower power, longer duration pulse because the beam current slightly exceeded the necessary start current condition of 7 kA. The lower current from the carbon fiber cathode was due to an error in the design of emission area.

3. THE HARD-TUBE MILO

The MILO is a crossed field device which generates a π-phase shift between adjacent cavities. The modulated electron beam is formed as the magnetically insulated flow $\underline{E}\times\underline{B}$ drifts beneath the cavities. Because of significant rf pulse shortening (see Fig. 3) observed in the original version of the Phillips Laboratory MILO [6-7], it was decided to build an all stainless steel, brazed version of the tube. This eliminates all the finger stock rf joints which were shown to breakdown in both the RKO and the MILO, plus it gives us the ability to investigate the impact of conventional conditioning techniques such as vacuum bake-out and rf discharge cleaning on the power and pulse length generated by the MILO.

The brazed tube, which we call the Hard-Tube MILO (HTMILO), is shown in Fig. 4. It is composed of two choke cavities which provide a well defined rf reflecting boundary for the backward traveling wave, a four cavity slow-wave structure, extractor gap, and coaxial extractor/beam dump. The choke cavities have a different passband than the MILO cavities and so reflect the backward traveling wave in the proper phase to constructively add to the forward traveling wave. The HTMILO is identical to the original tube except in two respects. First of all, the extractor is supported by six quarter-wavelength stubs rather than by four legs making gravity contact with the outer conductor wall. Secondly, the HTMILO has a tapered cathode shank in the choke vane region, while the original MILO had a constant-radius cathode over the entire length of the tube. Both MILOs employee a velvet cathode which runs from the upsteam edge of the last choke vane to the downstream end of the cathode shank. We show below that changing to a tapered shank in the choke vane region allowed the HTMILO to increase its output power to 1.8 GW, while tripling the pulse duration shown in Fig. 3.

Initial operation with the HTMILO used a constant-radius cathode shank under all the vanes, and the tube showed no improvement in performance over the original MILO. By using silicon PIN diode x-ray detectors, we observed that (1) the x-ray signature of the last choke vane was increasing late in the beam pulse, and (2) the x-ray signature of the electron beam dump was falling well before the end of the beam pulse. These two pieces of data indicated that magnetic insulation was being lost late in the beam pulse. In addition, we observed x-ray signatures from the first two choke vanes similar to that from the last choke vane indicating that unwanted electron emission was occurring in this region. Following several PIC simulations and some electrostatic calculations of the applied electric fields, we found that the electric field was sufficient to cause emission from the bare metal cathode shank below the choke vanes. By simply tapering the cathode geometry under the choke vanes (see Figs. 4 and 5), we eliminated this spurious electron emission, improved the launching of the magnetically insulated flow, and enabled the rf pulse to remain on almost to the conclusion of the electron beam pulse (see Fig. 6).

4. CONCLUSIONS AND FUTURE WORK

At this time both the HTMILO and injection-locked RKO produce rf pulses which terminate at or near the end of the electron beam pulse. We will soon complete upgrades to our present pulse power system to the following parameters: 500 kV, 5 Ω, 600 nsec. This will enable investigation of longer electron beam and rf pulses. The RKO will be brazed to overcome the arcing of the finger-stock joints, and the HTMILO will have an optimized, brazed extractor plus a new velvet cathode with hidden triple points to improve its performance. We are also planning to use a 4 ft diameter by 10 ft long vacuum bell jar to reduce the rf electric field stress on the vacuum-air interface by a factor of 6.

Acknowledgment

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Fig. Captions

Fig. 1. Drawing of the injection-locked RKO.

Fig. 2. Data showing the high power, high energy rf pulse from the carbon cathode driven RKO.

Fig. 3. Rf pulse shortening observed in original MILO [7].

Fig. 4. The Hard-Tube MILO experimental configuration.

Fig. 5. TWOQUICK simulation results for (a) the original HTMILO cathode configuration and (b) tapering the cathode shank under the choke vanes.

Fig. 6. HTMILO experimental results using configuration shown in Fig. 5b.

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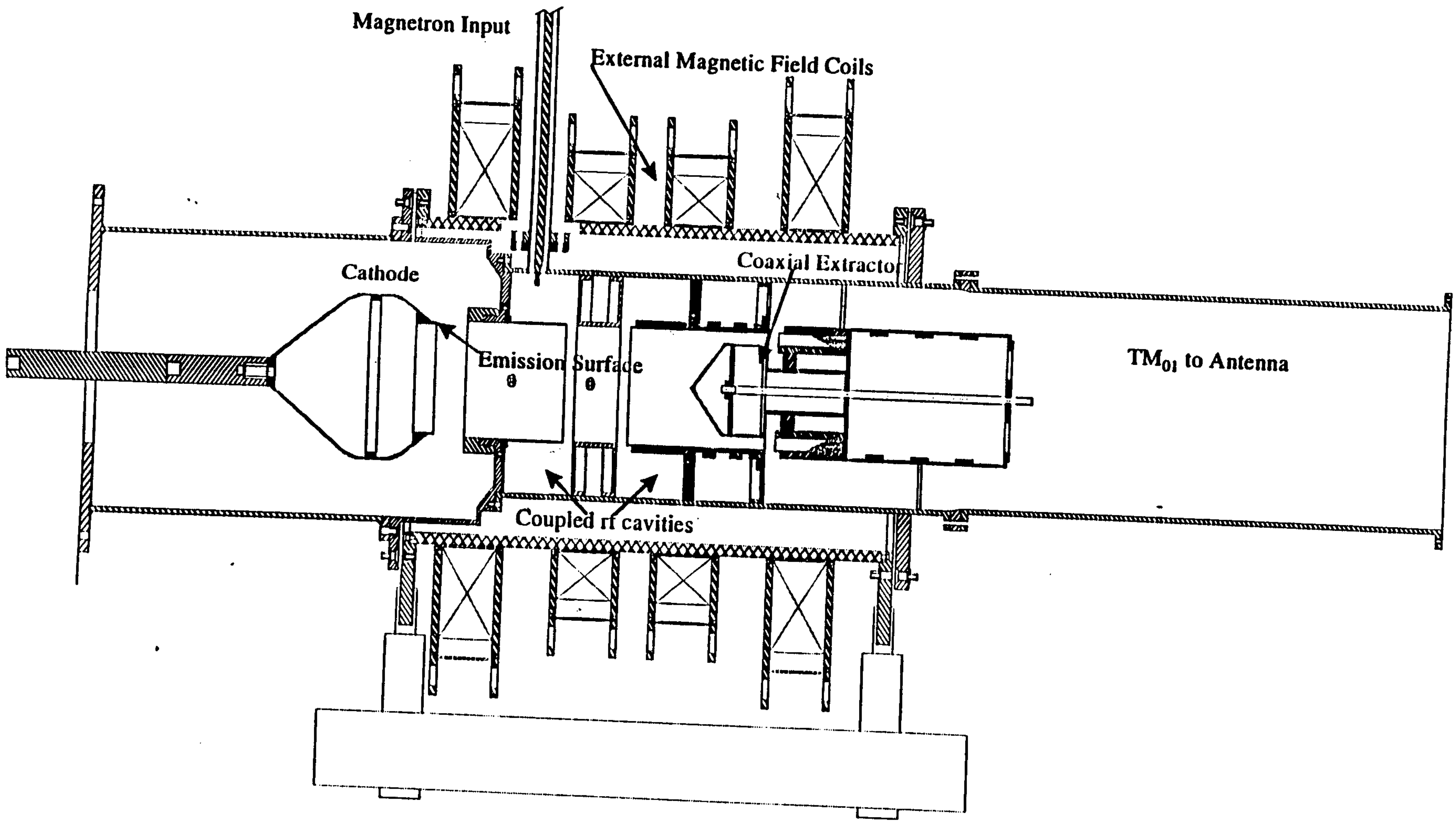
f= 1.27 GHz

Beam Current= 10 kA
Pulse Duration= 150 nsec



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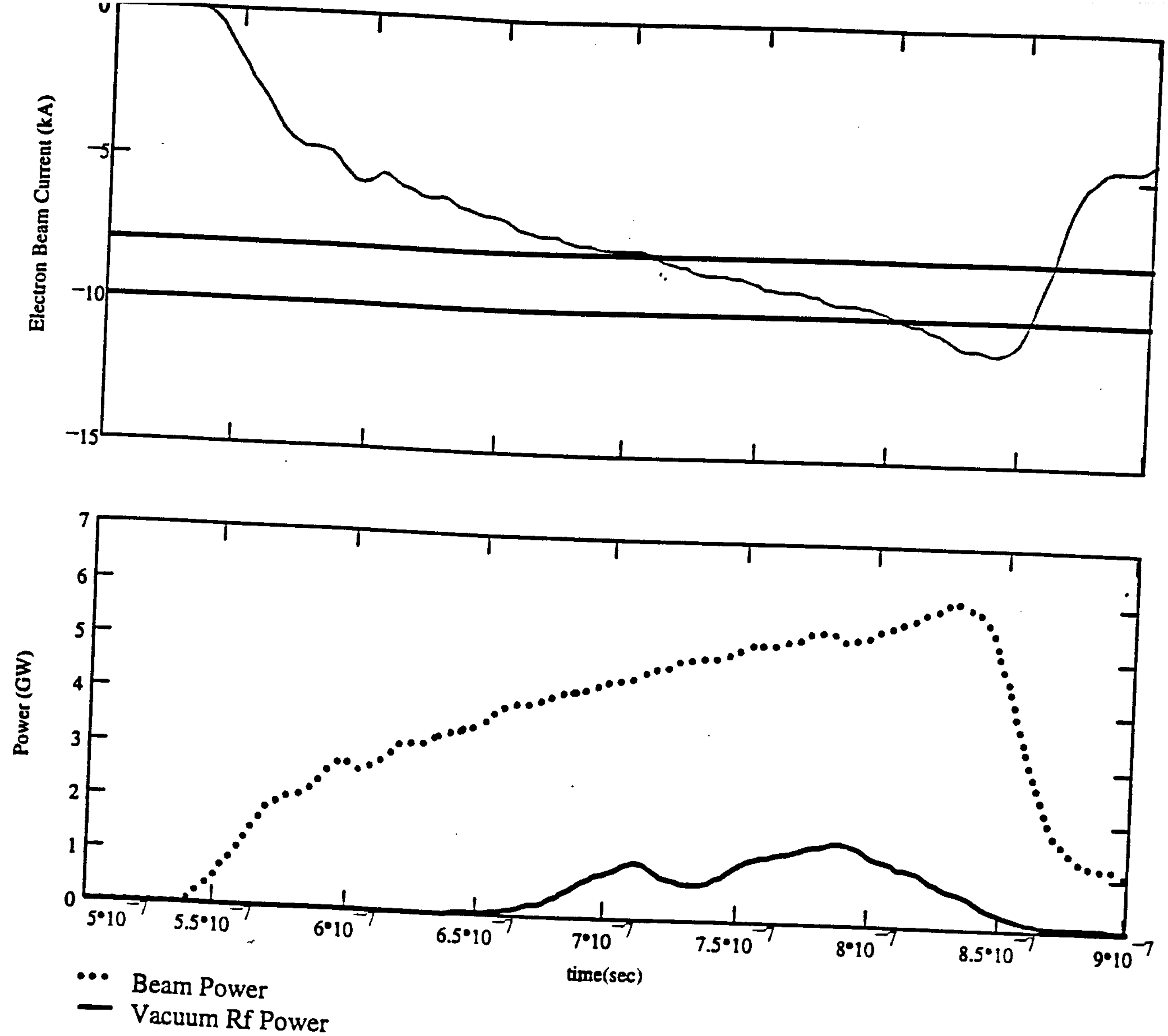
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−10
−15
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6
5
4
3
2
1
0
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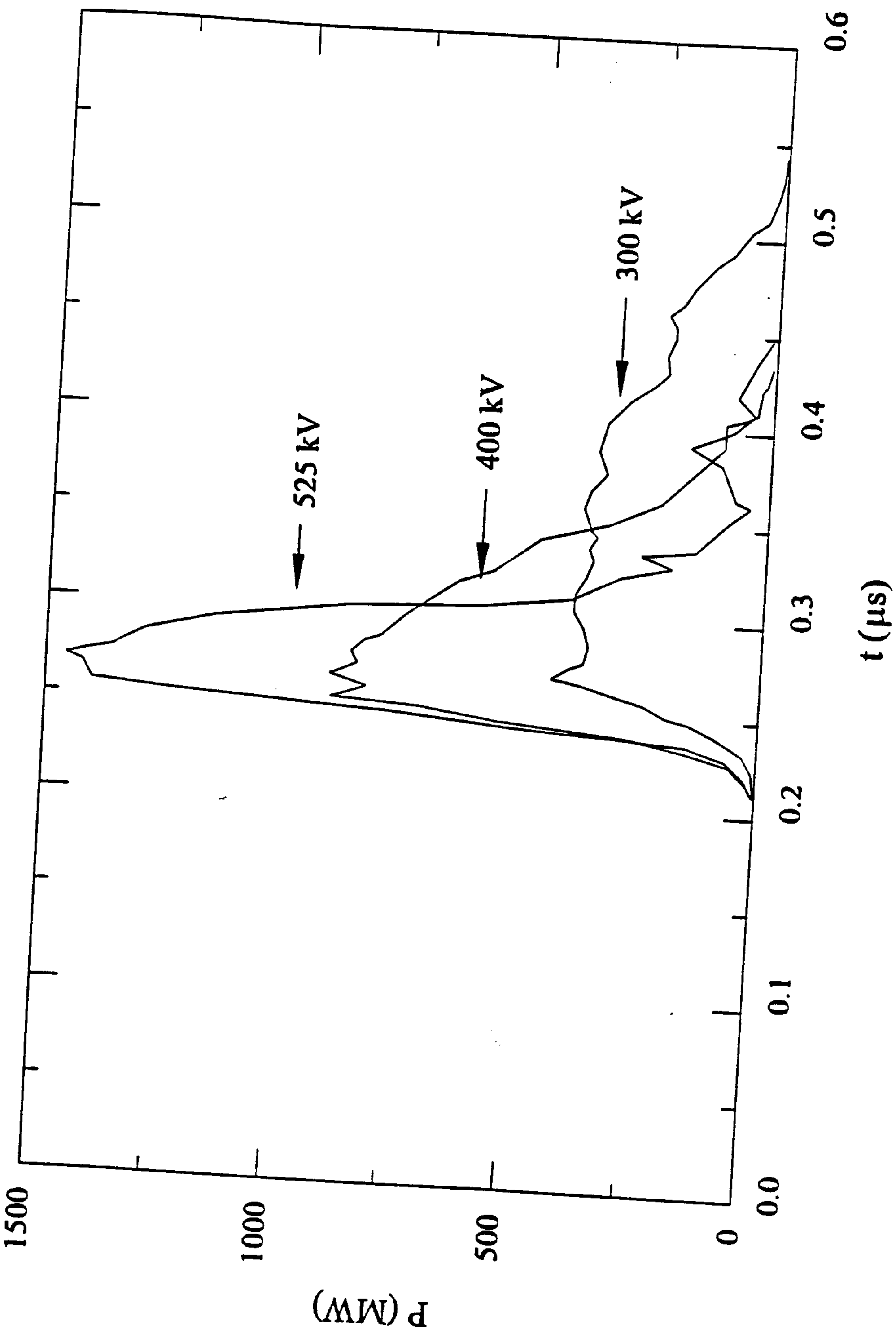
5.5•10⁻⁷
6•10⁻⁷
6.5•10⁻⁷
7•10⁻⁷
7.5•10⁻⁷
8•10⁻⁷
8.5•10⁻⁷
9•10⁻⁷
time(sec)
Beam Power
Vacuum Rf Power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1000
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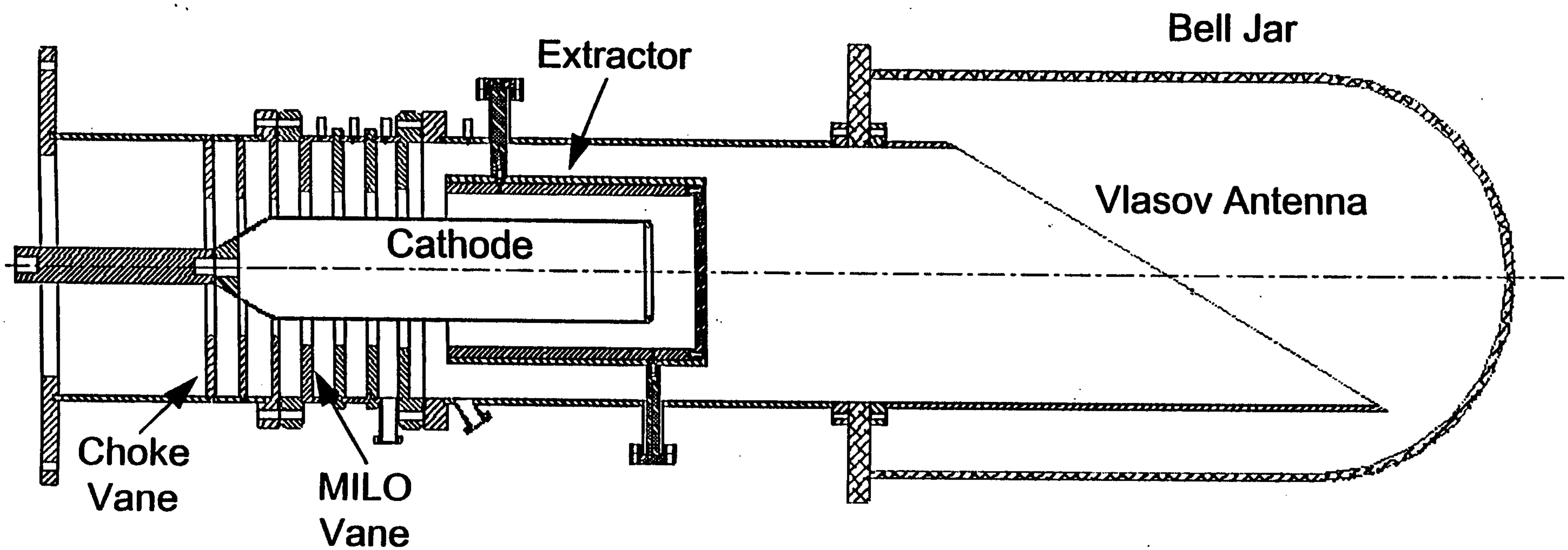
400 kV
300 kV



Operating Parameters: Diode Voltage = 500 kV Load Current = 60 kA
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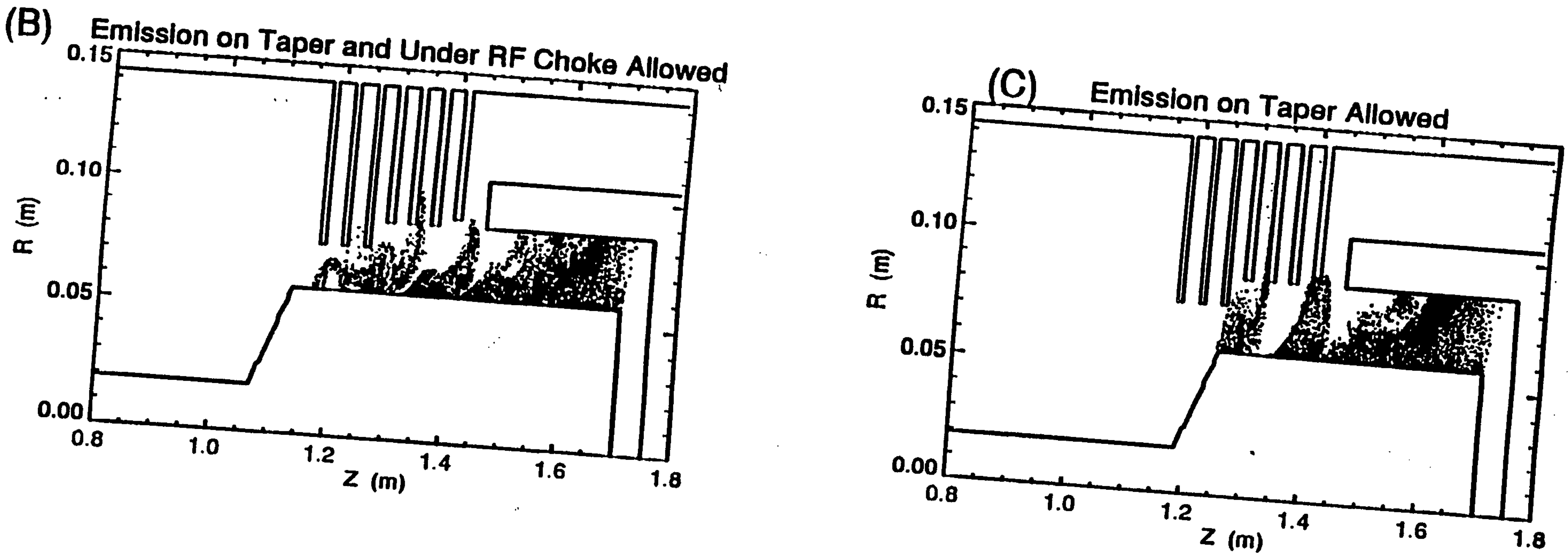
f = 1.2 GHz


(B)
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0.05
0.00
0.8
1.0
1.2
1.4
1.6
1.8
Z (m)
(C)
Emission on Taper Allowed
R (m)
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0.00
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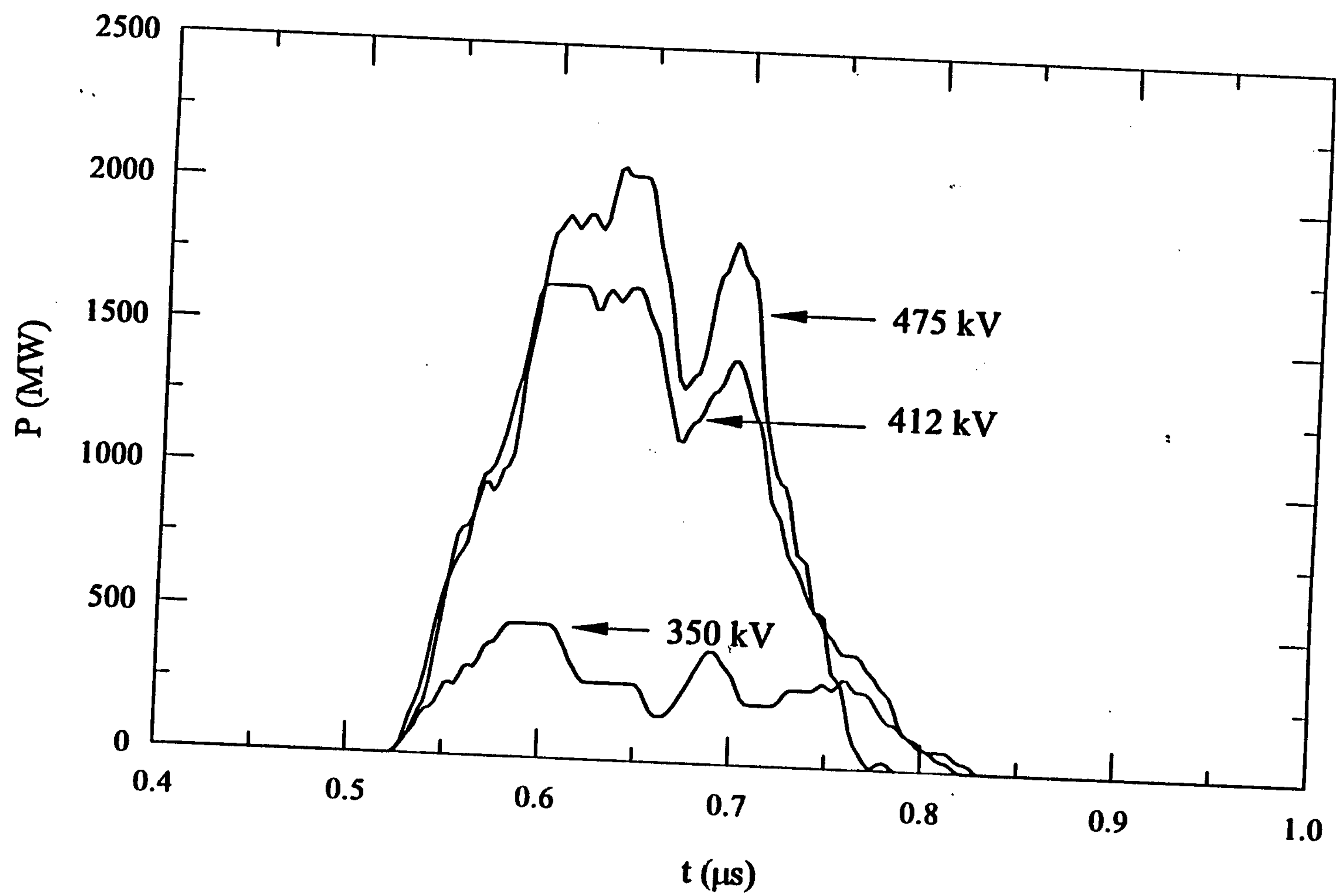
1.8
Z (m)

KIM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